

(12) **UK Patent Application** (19) **GB** (11) **2 207 522 A** (13)  
 (43) Application published 1 Feb 1989

(21) Application No 8717697

(22) Date of filing 25 Jul 1987

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(51) INT CL<sup>4</sup>  
**G02B 26/08**

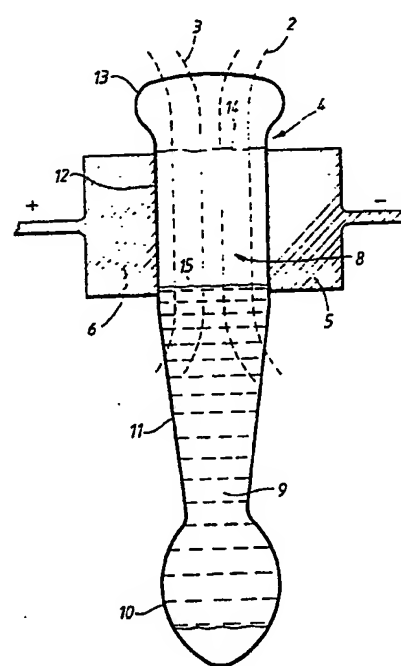
(52) Domestic classification (Edition J):  
**G2J GDB**

(56) Documents cited  
**None**

(58) Field of search  
**G2J**  
**Selected US specifications from IPC sub-class**  
**G02B**

(54) **Integrated optical coupling device using movable liquid**

(57) Light energy is selectively coupled between two adjacent wave guide channels 2,3 co-extensive in a surface layer of a substrate by causing the overlying medium 8, to be either a dielectric liquid 9 or air. This is achieved by moving the dielectric liquid selectively over and away from the wave guide channels 2,3, preferably using the electro-capillary effect between two electrodes 5,6.



**FIG.3.**

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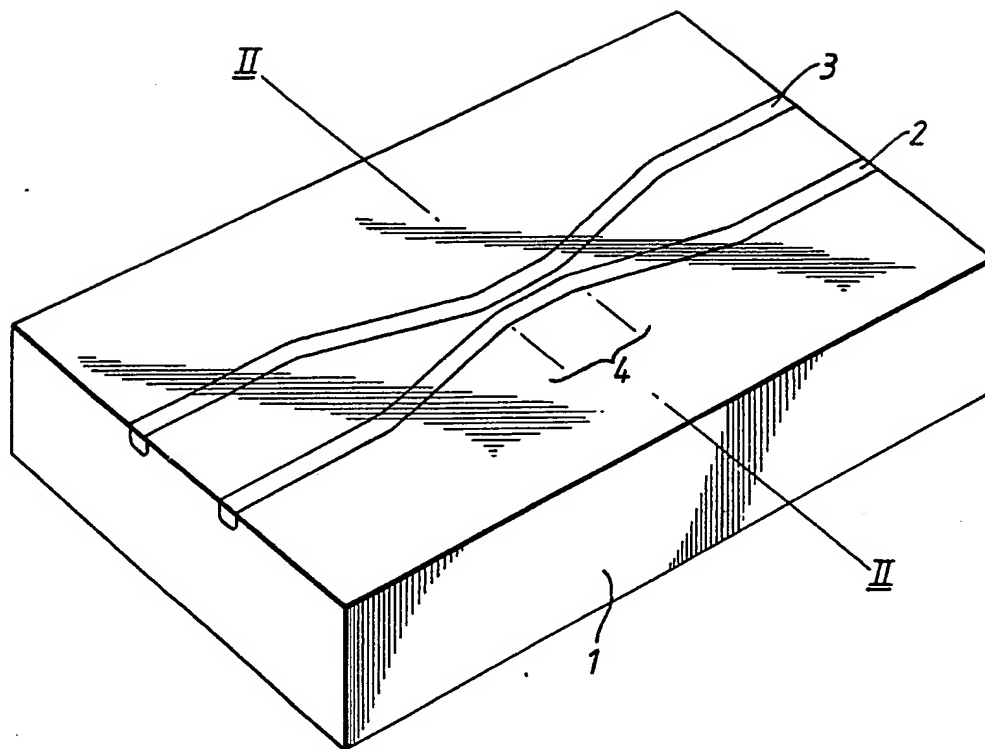


FIG. 1.

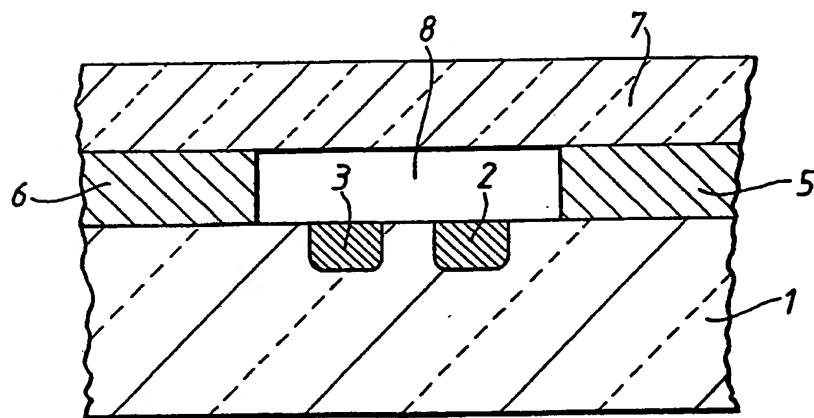
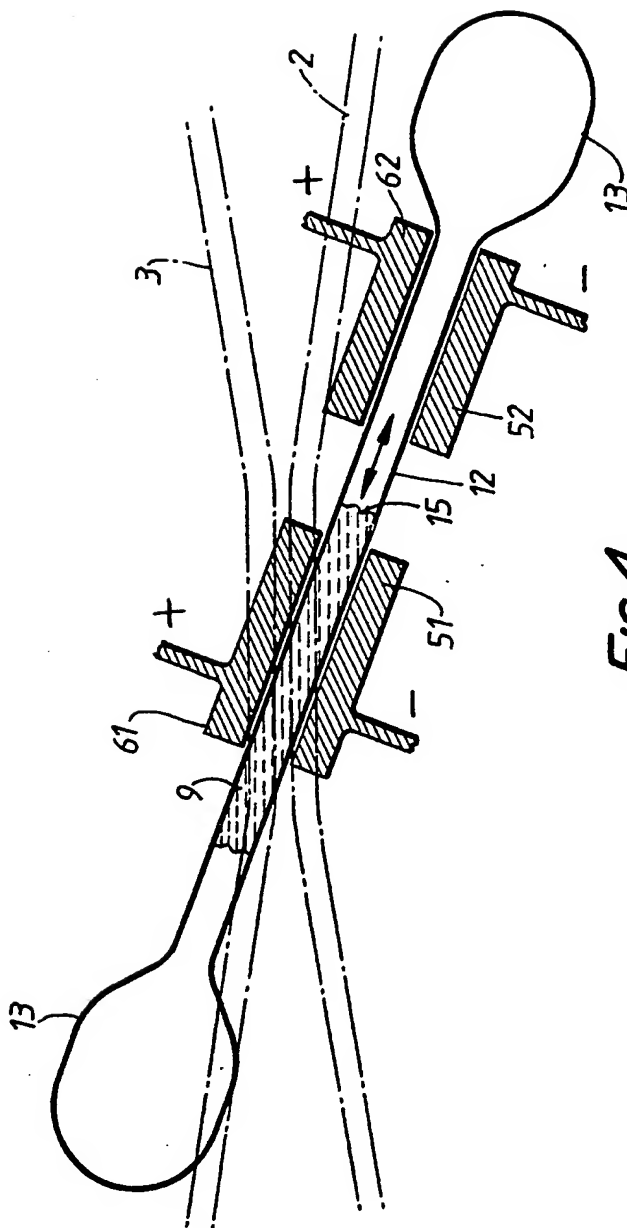


FIG. 2.



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Integrated Optical Coupling Device

This invention relates to an integrated optical device in which light energy in two wave guide channels is selectively coupled. The invention is particularly useful in directional couplers, but may also be used in two mode interferometer devices or "B.O.A." switches, and in other devices such as X switches.

Conventionally, most optical switching is achieved using the electro-optic effect, by changing the refractive index of a material such as lithium niobate as a function of the applied electric field. In the case of wave guide channels such as ion-exchange glass, which are not susceptible to the electro-optic effect, an alternative switching means is necessary.

The invention provides an integrated optical device comprising two adjacent wave guide channels co-extensive in a coupling plane the channels having a common interface with a region overlying the coupling plane, a dielectric liquid contained in a volume including the overlying region, and switch means for moving the dielectric liquid selectively to vary the proportion of the interface area which is overlain by the dielectric liquid, whereby light is selectively coupled between the channels. This invention uses the phenomenon that the refractive index of a region overlying two or more further regions of

different refractive indices affects the extent to which light energy is coupled between those further regions. In this case, the refractive index is changed by physically moving a dielectric liquid thus selectively replacing the liquid at at least part of the said interface with a medium such as air with a different refractive index.

The device may for example be a directional coupler, the channels being parallel and spaced in the coupling plane.

Preferably, the switch means comprises means for selectively applying an electro-magnetic field across the dielectric liquid to attract it towards or away from the said interface by the electro-capillary effect.

In order that the invention may be better understood, two embodiments of the invention will now be described, by way of example only, with reference to the accompanying diagrammatic drawings, in which:

Figure 1 is a perspective view from above of the glass substrate of a directional coupler, in which the aspect ratio is greatly exaggerated;

Figure 2 is a section, to an enlarged scale, taken along the line II-II of Figure 1, and further showing overlying features for varying the coupling of the light energy between two channels formed in the substrate;

Figure 3 is a plan view of the directional coupler device of Figure 2; and

Figure 4 is a plan view of an alternative form of

directional coupler device incorporating the substrate of Figure 1.

A directional coupler device selectively couples the light waves travelling in two waveguides, so as to switch light from one to the other.

Two optical wave guide channels 2, 3 are formed by ion exchange in a surface layer of a glass substrate 1. The channels 2, 3 are generally parallel and spaced apart, except over intermediate sections where the channels are bent towards each other. At a coupling region 4, the adjacent wave guide channels are parallel and close together. Typically the width of the coupling region, across both channels, is  $10\text{ }\mu\text{m}$ , and its length several hundred microns. The device could even be centimetres long. With reference to Figures 2 and 3, an electrode layer comprising metal electrodes 5, 6 of opposite polarity, typically  $2\text{ }\mu\text{m}$  thick, is superimposed on the glass substrate 1. The electrodes are disposed on opposite sides of the pair of co-extensive wave guide channels 2, 3, and extend parallel to the channels. A protective glass layer 7 is disposed over the electrode layer.

The region 8 overlying the substrate surface, and bounded by the electrodes 5, 6, is part of an enclosed volume, bounded by the glass substrate 1 and the protective layer 7, consisting of an air reservoir 13, a

dielectric liquid reservoir 10, a tapering intermediate portion 11 and a straight intermediate portion 12. An air-pressure equalisation channel (not shown) links the two reservoirs 10,13.

The dielectric liquid 9 preferably has a high dielectric constant and a low viscosity, and may for example be xylene or bromonaphthalene. The remainder of the enclosed volume not occupied by the dielectric liquid 9 is filled with air.

The tapering portion 11 of the volume enclosure causes the dielectric liquid 9 to be continuously urged into the liquid reservoir 10 under the capillary effect. This is an application of the invention disclosed and claimed in our copending UK Patent Application No. 8711211. At equilibrium, with no voltage applied to the electrodes 5, 6, the interface 15 between the dielectric liquid 9 and the air in the air reservoir 13 is at one end of the straight intermediate portion 12, i.e. at one end of the coupling region 8, so that there is no dielectric liquid overlying the waveguide channels in the coupling region.

When a constant or alternating voltage is applied across the electrodes 5, 6, the dielectric liquid 9 is urged into the region between the electrodes under the electro-capillary effect, in opposition to the capillary action of the tapering portion 11. The interface 14 in this region between the dielectric liquid 9 and the air is



then at the opposite end of the coupling region 8, so that the dielectric liquid 9 overlies the waveguide channels. When the applied voltage is removed again, the dielectric liquid 9 is restored to its original position 15 under the capillary action of the tapering portion 11.

Thus the refractive index of the medium in the enclosed volume 8 at the coupling region may be varied selectively between that of the dielectric liquid 9 and that of air. The coupling of light energy between the channels 2, 3 is a function of this refractive index, so that the application of different voltages to the electrodes 5, 6 selects the degree of coupling between the channels. By varying the applied voltage, the degree of overlap of the wavelength channels at the coupling region 4 by the dielectric liquid 9 may be varied, to enable the degree of coupling to be selected from a continuous range. To achieve switching of the light from one channel to the other, the coupling must be such that the integral, taken over the length of the coupling region, of the coupling strength changes by  $\pi/2$  when the liquid is moved between two stable positions (corresponding to the two states of the switch). The relevance of coupling strength  $k$  is described for example in "Improved Coupled-Mode Equations for Dielectric Guides" by E. Marsatili, IEEE Journal of Quantum Electronics, Vol. QE-22, No. 6, June, 1986.

Alternative methods of moving the dielectric liquid may be employed; there may for example be a further pair

of electrodes for providing the restoring source using the electro-capillary effect, in which case the tapering portion 11 is not required. In this case, it may not be necessary to maintain a potential difference across a pair of electrodes in order to hold the dielectric liquid in position, since there would then usually be no biasing force acting constantly on the liquid. Pulses may be used to drive the electrodes, to change the position of the liquid.

The restoring force could alternatively be provided by isolating the reservoirs 10, 13 and allowing a back pressure to build up in the air reservoir 13.

A second embodiment of the invention will now be described with reference to Figures 1 and 4, in which corresponding parts are labelled similarly. This directional coupler operates by varying the propagation constants  $\beta$  of the two waveguides differentially over the coupling region, i.e. by varying the relative speeds of light through them. This technique is described in principle in "Switched Directional Couplers with Alternating  $\Delta\beta$ " by H. Kogelnik, et al, IEEE Journal of Quantum Electronics, Vol. QE-12, No. 7, July, 1976. This is achieved, according to this embodiment of the invention, by varying the relative proportions of the waveguide channel areas which are overlain by the dielectric liquid, i.e. by moving a bead of the dielectric

liquid transversely of the channels 2,3, of the coupling region 4 (as well as, or instead of, moving it longitudinally as in Figure 3).

The enclosed volume for the dielectric liquid 9 consists of two air reservoirs 13 joined by a long, straight channel 12 inclined at a very small angle, say between  $1^{\circ}$  and  $5^{\circ}$ , to the longitudinal axis of symmetry of the device. A first pair 51, 61 of electrodes is disposed over the substrate 1 surface on either side of the straight channel 12, the electrodes extending over the coupling region 4. A second pair 52, 62 of electrodes is disposed further down the straight channel 12, nearer one of the air reservoirs 13. An electronic control system (not shown) supplies pulses to the appropriate electrode pair to attract the liquid 9 to any one of at least two stable positions, each of which gives rise to a different value of  $\Delta\beta$ . In the use of a simple switch, there are two stable positions: the switch operates between positions giving rise to one state of  $\Delta\beta$  and a state of  $\Delta\beta$  reversal. For example, at one the liquid may be clear of the coupling region; and at the other the liquid may lie over a larger proportion of one channel 2 than the other 3.

In neither embodiment of the invention is it essential for the channels to be parallel at the coupling region, nor for the electrodes to be symmetrically disposed. Both the coupling strength  $k$  and the

differential propagation constant  $\Delta\beta$  can be varied by arranging, for example in the embodiment of Figure 3, that waveguide channel 2 diverges from the other waveguide channel 3 and from the straight intermediate portion 12.

Although it is convenient in either embodiment of the invention, to have a liquid-air interface 14, 15, this could instead be a liquid-liquid interface, i.e. there could be two dielectric liquids contained within the volume 10, 11, 12, 13, provided that those liquids are not miscible.

While the invention is particularly useful in optical devices in which the channels are of ion-exchange glass, this is of course not essential: the channels could for example be created using chemical vapour deposition and etching techniques.

While the invention has been illustrated by means of a directional coupler device, the invention is applicable to any integrated optical devices in which light is coupled between two adjacent waveguide channels. In a two-mode interferometer switch (also known as a B.O.A. switch) the channels are integral at the coupling region but are otherwise separate. In an X-switch, the channels cross at the coupling region. The invention may be applied by moving a dielectric liquid over the channels where they are co-extensive, either where they are integral or where they are close together, or both.

CLAIMS

1. An integrated optical device comprising a substrate in a surface layer of which are formed two waveguide channels which are optically coupled at a coupling region, a dielectric liquid contained in a volume bounded in part by the surface layer at the coupling region, and switch means for moving the dielectric liquid selectively to vary the degree of overlap by the dielectric liquid of the waveguide channels at the coupling region.
2. An integrated optical device according to Claim 1, wherein the coupling region constitutes a directional coupler, the channels being parallel and spaced in the coupling region.
3. An integrated optical device according to Claim 1, wherein the coupling region constitutes a two-mode interferometer switch, the channels being integral at the coupling region but otherwise separate.
4. An integrated optical device according to Claim 1, wherein the coupling region constitutes an X switch, the channels crossing at the coupling region.
5. An integrated optical device according to any preceding claim, wherein the switch means comprises a pair of electrodes for applying selectively an electric field across the dielectric liquid to attract it towards or away from the coupling region by means of the electro-capillary effect.

6. An integrated optical device according to Claim 5, comprising a further pair of electrodes positioned such that the application of a voltage signal to either electrode pair moves the dielectric liquid to a corresponding stable position, the stable positions being such as to cause different degrees of the said overlap of the waveguide channels.

7. An integrated optical device according to Claim 5, comprising means for continuously biasing the dielectric liquid in opposition to the attractive force provided by the pair of electrodes, whereby the dielectric liquid is movable between different stable positions by the application of different corresponding potential differences across the electrodes.

8. An integrated optical device according to Claim 7, wherein the biasing means acts by applying fluid pressure to the dielectric liquid.

9. An integrated optical device according to Claim 7, wherein the said volume is tapered so as to provide a capillary effect which biases the dielectric liquid towards the narrower portion of the volume, in opposition to the attraction caused by the said electro-capillary effect.

10. An integrated optical device according to any preceding claim, wherein the remainder of the said volume which is not occupied by the dielectric liquid is occupied by air, so that the switch means selectively causes either

air or the dielectric liquid to overlies the waveguide channels at the coupling region.

11. An integrated optical device according to any preceding claim, wherein the switching means moves the dielectric liquid lengthwise of the waveguide channels whereby to vary the length of both channels which is overlain by the dielectric liquid, to vary correspondingly the integral of the coupling coefficient between the waveguide channels taken over the length of the coupling region.

12. An integrated optical device according to any of Claims 1 to 10, wherein the switching means moves the dielectric liquid transversely of the waveguide channels whereby to vary their differential light propagation constants so as to switch light correspondingly between the channels.

13. An integrated optical device substantially as described herein with reference to the accompanying drawings.